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SUMMARY

A method of Gemini-Agena station keeping using a connecting tether has been investigated both by analysis and by static and moving-base piloted simulations. The method involves spinning the tethered combination about its common center of mass so that tension is maintained in the cable and the vehicles remain close to each other without contact. The analytical study shows that the tethered system is inherently stable while spinning about its axis of maximum moment of inertia. The simulations indicate that pilots can perform the maneuver and can minimize fuel usage with either of the two piloting techniques studied.

INTRODUCTION

The tethering and rotation of two vehicles in space provides an efficient method of station keeping (flying close to another vehicle for prolonged periods of time) and an artificial gravity field. This study considered the tethering of a manned Gemini vehicle to an unmanned Agena vehicle. The tether used was a flexible cable which was to be attached to the vehicle by an astronaut during an extravehicular maneuver. The pilot of the Gemini was then to remove the slack from the cable by translation of the Gemini. When the cable was completely extended, the system was spun about its common center of mass by the lateral thrusting of the Gemini vehicle. See figure 1(a).

A three-phase study has been conducted in order to investigate the basic problems encountered in this maneuver. First, a stability analysis was made in which several possible configurations of the tethered system were analyzed. Next, a five-degree-of-freedom planar analysis of the Gemini-Agena tethered systems was conducted by using the Langley rendezvous docking simulator for the moving-base simulation of this problem. Finally the Langley visual rendezvous simulator was used for the fixed-base simulation of this problem. This simulator used a television projection of an Agena model superimposed on a screen along with a star background and an earth horizon as the display presented to the pilot.

Once the stability of the tethered system was ascertained, the main emphasis of the investigation was to determine the pilot's ability to maintain an arbitrary amount of tension of the cable by spinning the system, to control the attitudes of the Gemini, and to damp the fore-and-aft oscillations of the system with a minimum use of fuel.

SYMBOLS

A,B nondimensional coefficients

D operator, d/dt

F_X, F_Y translation control forces, lb (N)

I_X, I_Y, I_Z principal body axis moments of inertia, slug-ft^2 $\left(\text{kg-m}^2\right)$

K cable spring constant, lb/ft (N/m)

l moment arm, ft (m)

l_c unstretched cable length plus the moment arm, ft (m)

Δl_c cable slack, ft (m)

M_ϕ, M_θ, M_ψ attitude control moments, lb-ft (N-m)

m_A mass of Agena, slugs (kg)

m_G mass of Gemini, slugs (kg)

m_t total translation fuel used, slugs (kg)

p,q,r body axis angular rates, radians/sec

r' body axis yaw rate with respect to cable, radians/sec

s distance from center of mass of system to Gemini center of gravity, ft (m)

$s_{A,G}$ distance between center of gravity of Gemini and Agena, ft (m)

T tension, lb (N)

t	time, sec
x,y,z	distances along X,Y,Z inertial axes, ft (m)
x',y',z'	distances along X',Y',Z' intermediate axes, ft (m)
x_B,y_B,z_B	distances along X_B,Y_B,Z_B body axes, ft (m)
α	angle between cable and inertial reference, radians
ψ,θ,ϕ	Euler angles, radians

Subscripts:

A	refers to Agena vehicle
G	refers to Gemini vehicle

Dots over quantities denote derivatives with respect to time. Arrow over symbol denotes vector.

STABILITY ANALYSIS

In the current study of a rotating system, it was necessary to study the distribution of moments of inertia that would produce a stable system. To accomplish this study, the moment equations about the vehicle body axis are written

$$I_X\dot{p} + \left(I_Z - I_Y\right)qr = 0 \tag{1a}$$

$$I_Y\dot{q} + \left(I_X - I_Z\right)pr = 0 \tag{1b}$$

$$I_Z\dot{r} + \left(I_Y - I_X\right)pq = 0 \tag{1c}$$

where it is assumed that all products of inertia are zero.

Equations (1a), (1b), and (1c) describe the spinning of a rigid body without a tether. The solution to these ideal equations yields neutral stability if the axis about which the body is spinning is the axis of either the maximum or minimum moment of inertia, but it yields instability if that axis is an axis of the intermediate moment of inertia.

The problem of interest here is a tethered system. The addition of a tether produces a restoring moment because of the presence of the cable. This tether is assumed to have l/l_c small, no mass, and no torsion. Within small angle approximations the moment is given by $-Tl\theta$ and $-Tl\psi$ added to the right-hand side of equations (1b) and (1c), respectively, where θ is the angle between the X_B body axis and the x',y' plane as shown in figure 1 and ψ is the angle in the x',y' plane between the X'-axis and the X_B body axis.

If a restricted case in which ψ and θ are small is assumed, but some roll angle ϕ exists, and the tethered system has some rotation rate $\dot{\alpha}$, within small angle approximations,

$$p \doteq p \tag{2a}$$

$$q \doteq \dot{\alpha} \sin \phi \tag{2b}$$

$$r \doteq \dot{\alpha} \cos \phi \tag{2c}$$

Therefore substituting equations (2a), (2b), and (2c) into equations (1a), (1b), and (1c), respectively, and adding the cable restoring terms results in

$$I_X\dot{p} + \left(I_Z - I_Y\right)\dot{\alpha}^2(\cos \phi \sin \phi) = 0 \tag{3a}$$

$$I_Y\dot{q} + \left(I_X - I_Z\right)\dot{\alpha}p \cos \phi = -Tl\theta \tag{3b}$$

$$I_Z\dot{r} + \left(I_Y - I_X\right)p\dot{\alpha} \sin \phi = -Tl\psi \tag{3c}$$

In this case it can be seen from equation (3a) that if $I_Y > I_Z$, the coefficient $\left(I_Z - I_Y\right)\dot{\alpha}^2$ is negative and therefore there can be roll divergence. It can also be seen from equation (3c) that if $\phi \approx 0$, which is a good approximation if there is no roll instability, static stability will result in yaw.

If, on the other hand, both ϕ and ψ are assumed to be small, which is a good assumption if the system is stable, yaw can be assumed to be restricted so that equation (3c) can be replaced by $r = \dot{\alpha} = \text{Constant}$. Using small angles in the Euler angle equations yields

$$p = \dot{\phi} - \dot{\alpha}\theta \tag{4}$$

$$q = \dot{\theta} + \dot{\alpha}\phi \tag{5}$$

The substitution of equations (4) and (5) into equations (1a) and (1b) along with the restoring moment due to the cable results in

$$\left(\ddot{\phi} - \dot{\alpha}\dot{\theta}\right) + \left(\frac{I_Z - I_Y}{I_X}\right)\dot{\alpha}\left(\dot{\theta} + \dot{\alpha}\phi\right) = 0 \tag{6}$$

$$\left(\ddot{\theta} + \dot{\alpha}\dot{\phi}\right) + \left(\frac{I_X - I_Z}{I_Y}\right)\dot{\alpha}\left(\dot{\phi} - \dot{\alpha}\theta\right) = -\frac{Tl\theta}{I_Y} \tag{7}$$

Let

$$A = \frac{I_Z - I_Y}{I_X}$$

$$B = \frac{I_Z - I_X}{I_Y}$$

The characteristic equation for equations (6) and (7) becomes

$$\begin{vmatrix} D^2 + A\dot{\alpha}^2 & -(1 - A)\dot{\alpha}D \\ (1 - B)\dot{\alpha}D & D^2 + \frac{Tl}{I_Y} + B\dot{\alpha}^2 \end{vmatrix} = 0$$

which results in

$$D^4 + \left[\frac{Tl}{I_Y} + (1 + AB)\dot{\alpha}^2\right]D^2 + A\dot{\alpha}^2\left(\frac{Tl}{I_Y} + B\dot{\alpha}^2\right) = 0 \tag{8}$$

$$D = \pm\left\{\frac{-\left[\frac{Tl}{I_Y} + (1 + AB)\dot{\alpha}^2\right] \pm\sqrt{\left[\frac{Tl}{I_Y} + (1 + AB)\dot{\alpha}^2\right]^2 - 4A\dot{\alpha}^2\left(\frac{Tl}{I_Y} + B\dot{\alpha}^2\right)}}{2}\right\}^{1/2} \tag{9}$$

In order to be stable the characteristic equation must not contain real positive roots. Thus, the requirement for stability becomes

$$\left.\begin{aligned}
&\frac{Tl}{I_Y} + (1 + AB)\dot{\alpha}^2 \geqq 0 \\
&A\dot{\alpha}^2\left(\frac{Tl}{I_Y} + B\dot{\alpha}^2\right) \geqq 0 \\
&\left[\frac{Tl}{I_Y} + (1 + AB)\dot{\alpha}^2\right]^2 \geqq 4A\dot{\alpha}^2\left(\frac{Tl}{I_Y} + B\dot{\alpha}^2\right)
\end{aligned}\right\} \tag{10}$$

Either of two cases will satisfy these conditions:

Case I:

$$0 \leqq A \leqq 1 + \frac{I_Y\dot{\alpha}^2}{Tl}$$

when

$$\frac{Tl}{I_Y} + B\dot{\alpha}^2 \geqq 0$$

Case II:

$$A \leqq 0$$

when

$$\frac{Tl}{I_Y} + B\dot{\alpha}^2 \leqq 0$$

Since $\frac{Tl}{I_Y} \geqq 0$, the following relationships are obtained:

For Case I: If

$$\left.\begin{aligned}
&0 \leqq \frac{I_Z - I_Y}{I_X} \leqq 1 + \frac{I_Y\dot{\alpha}^2}{Tl} \\
&I_Z - I_X \geqq -\frac{Tl}{\dot{\alpha}^2}
\end{aligned}\right\} \tag{11}$$

the system is neutrally stable.

For Case II: If

$$I_Z \leqq I_Y \qquad I_Z - I_X \leqq -\frac{Tl}{\dot{\alpha}^2} \tag{12}$$

the system is neutrally stable.

If neither of these conditions is met, the system is unstable. If the restoring moment is added to the roll axis X instead of to the pitch axis, x replaces y and y replaces x in inequalities (11) and (12).

To illustrate the stability conditions that can be encountered in the tethered system, several different possible configurations were considered. It was assumed that the vehicle had different moments of inertia for each of its principal axes. The six examples shown in table I cover the conditions that exist when the tether is attached at different points on the vehicle. Configuration I defines the situation of attaching the tether to the small end of the vehicle and establishing the system spin so that the axis of maximum moment of inertia of the vehicle is alined with the spin vector. Configuration II is for case where the tether is attached to the long side of the vehicle and with the axis of minimum moment of inertia alined with the spin vector. The six configurations cover the six possible arrangements. Both tension and spin rate ($\dot{\alpha}$) are assumed to be constant.

TABLE I.- INERTIA CONFIGURATIONS

Configuration	I_X		I_Y		I_Z	
	slugs-ft^2	kg-m^2	slugs-ft^2	kg-m^2	slugs-ft^2	kg-m^2
I	1530	2074.4	4000	5423.2	4500	6101.1
II	4500	6101.1	4000	5423.2	1530	2074.4
III	1530	2074.4	4500	6101.1	4000	5423.2
IV	4000	5423.2	1530	2074.4	4500	6101.1
V	4500	6101.1	1530	2074.4	4000	5423.2
VI	4000	5423.2	4500	6101.1	1530	2074.4

Table II presents the results obtained when the test for stability (eqs. (11) and (12)) is applied to each of the cases.

TABLE II.- STABILITY OF EXAMPLE CONFIGURATIONS

[S, neutrally stable; U, unstable]

Configuration	No cable	Tether restoring moment (pitch)	Adding stability augmentation in roll
I	S	S	S
II	S	U	S
III	U	U	S
IV	S	S	S
V	U	S	S
VI	S	U	S

The second column presents the results for a spinning body with no restoring moments. The results presented in the third column are applicable to the tethered system and contain a restoring moment that is a function of the angle θ. Significant results shown are that configurations II and VI are unstable and configuration V is stable for the tethered system.

The results presented here correspond to the results presented in reference 1, in which the stability of rolling aircraft was studied. It is shown in reference 1 that for the conditions of configuration II, where the case of the rolling aircraft is equivalent to the tethered system, the addition of damping augmentation will not restore stability. It would be necessary to add attitude stabilization to a second axis to restore stability, as might be done by commanding the control system to respond to measured angles. Column four shows the results obtained when a restoring moment equal to that provided by the tether in the pitch axis is added to the roll equation. This addition restores stability for all cases that were unstable.

The particular example of the Gemini-Agena tethered system that is studied in the simulator experiments corresponds to configuration I.

DESCRIPTION OF THE SIMULATOR

Moving-Base Simulation

A simplified man-in-the-loop simulation of the tethered Gemini and Agena system was performed by using the Langley rendezvous docking simulator (RDS) (fig. 2), a moving-base simulator. A cable 75 feet (22.86 m) long was attached between the Gemini and Agena to be used as a visual cue by the pilot. The equations of motion were programed on an analog computer which was used to drive the visual display, in this case the Langley rendezvous docking simulator. The pilot physically senses the movement of the Gemini-Agena system and moves his translation and attitude hand controllers to control his vehicle in response to the movement. These deflections of the hand controllers are fed back to the computer which again drives the visual displays. The direct attitude control mode was simulated in this study. This sequence of events is shown in the block diagram in figure 3(a).

The assumptions made in the moving-base simulation were as follows:

(1) The two vehicles are in a gravity-free field

(2) The Agena was a point mass

(3) The Gemini had three degrees of attitude freedom and two degrees of translation freedom (fore, aft, and lateral)

(4) The tether was a flexible elastic cable 75 feet (22.86 m) long and had a spring constant of 200 lb/ft (29.18 N/m)

(5) The coordinate system was chosen so that the origin remains at the center of mass of the Gemini-Agena system and the axes always remain parallel to an inertially fixed reference coordinate system (see fig. 1(b))

(6) The Gemini had pairs of 100-pound (444.8 N) fore-and-aft thrusters and 100-pound (444.8 N) lateral thrusters. The lateral thrusters are canted 26° to fire through the Gemini center of gravity and to give a forward component when thrusting laterally.

The oscillatory rotation motions relative to the cable were presented to the pilot, but the steady rotation associated with the system rotation was not included in the motions presented to the pilot. It was felt that the steady rotation would only be of secondary importance as a cue to the pilot, and that it could therefore be omitted from the simulation.

Under these assumptions, the equations of motion used in this study were as follows:

For the Gemini vehicle before the cable becomes taut, the following translational equations apply:

$$\phi \approx 0$$

in translation equations since the pilot nulls roll,

$$\ddot{s} = s\dot{\alpha}^2 + \frac{1}{m_G\left(1 + \frac{m_G}{m_A}\right)}\left[\left(F_X - F_Y \sin 26^{\circ}\right)\cos\psi\cos\theta - \left(F_Y \cos 26^{\circ}\right)\sin\psi\right] \tag{13}$$

$$\frac{d}{dt}\left(s^2\dot{\alpha}\right) = \frac{s}{m_G\left(1 + \frac{m_G}{m_A}\right)}\left[\left(F_Y \cos 26^{\circ}\right)\cos\psi + \left(F_X - F_Y \sin 26^{\circ}\right)\cos\theta\sin\psi\right] \tag{14}$$

If the cable is taut, the following translational equations apply:

$$\ddot{s} = s\dot{\alpha}^2 + \frac{K}{m_G}\left[l_c - \left(1 + \frac{m_G}{m_A}\right)r\right] + \frac{1}{m_G\left(1 + \frac{m_G}{m_A}\right)}\left[\left(F_X - F_Y \sin 26^{\circ}\right)\cos\psi\cos\theta - \left(F_Y \cos 26^{\circ}\right)\sin\psi\right] \tag{15}$$

$$\frac{d}{dt}\left(s^2\dot{\alpha}\right) = \frac{s}{m_G\left(1 + \frac{m_G}{m_A}\right)}\left[\left(F_Y \cos 26^o\right)\cos \psi + \left(F_X - F_Y \sin 26^o\right)\sin \psi \cos \theta\right] \tag{16}$$

The moment equations where the body axis yaw rate is assumed to consist of two terms, the system angular rate $\dot{\alpha}$, and a body axis rate with respect to the cable r', are presented:

$$\dot{p} = \frac{M_\phi}{I_X} - \left(\frac{I_Z - I_Y}{I_X}\right)q(r' + \dot{\alpha}) \tag{17}$$

$$\dot{q} = \frac{M_\theta}{I_Y} - \frac{Tl}{I_Y}\sin \theta + \left(\frac{I_Z - I_X}{I_Y}\right)p(r' + \dot{\alpha}) \tag{18}$$

$$\dot{r}' = \frac{M_\psi}{I_Z} - \frac{Tl}{I_Z}\cos \theta \sin \psi - \left(\frac{I_Y - I_X}{I_Z}\right)pq \tag{19}$$

where M_ϕ, M_θ, and M_ψ are the Gemini attitude control moments about the roll, pitch, and yaw axes, respectively. Euler angle rates are given by the equations:

$$\dot{\psi} = r' \frac{\cos \phi}{\cos \theta} + q \frac{\sin \phi}{\cos \theta} \tag{20}$$

$$\dot{\phi} = p + \dot{\psi} \sin \theta \tag{21}$$

$$\dot{\theta} = q \cos \phi - r' \sin \phi \tag{22}$$

Also

$$T = 0 \qquad \left(\left[l_c - \left(1 + \frac{m_G}{m_A}\right)s\right] \geqq 0\right) \tag{23}$$

$$T = -K\left[l_c - \left(1 + \frac{m_G}{m_A}\right)r\right] \qquad \left(\left[l_c - \left(1 + \frac{m_G}{m_A}\right)s\right] < 0\right) \tag{24}$$

Tension is considered to act only along $\vec{s}$.

Note that an error in the potentiometer setting for the right-hand side of equations (14) and (16) caused the thrust to be approximately three times greater than the actual case. This error does not affect the general results, but it affects the length of time that it takes to spin the system up.

Two procedures were used by the NASA test pilots to produce sufficient spin-up to maintain 100 pounds (444.8 N) of tension in the cable and to use a minimum of fuel.

The first procedure was as follows:

(1) Remove slack from cable by firing forward thrusters

(2) Establish a system rotation by firing the Gemini lateral thrusters whose forward component (due to the 26° cant angle) was also used to advantage to null out separation velocity between Gemini and Agena

(3) Damp out fore-and-aft oscillation and attitude oscillation by use of the fore-and-aft and attitude thrusters.

The second piloting technique was as follows:

(1) Remove slack from cable by firing forward thrusters

(2) Arrest the separation velocity between the Gemini and Agena as the Gemini nears the end of the cable

(3) Yaw around 26° so that there will be no fore-and-aft component when the lateral thrust is applied to obtain the system rotation

(4) Damp out fore-and-aft oscillation and attitude oscillation by use of fore-and-aft and attitude thrusters.

Fixed-Base Simulation

A complete 12-degree-of-freedom simulation of the tethered Gemini-Agena system was conducted using the Langley visual rendezvous simulator (VRS). A schematic diagram of the equipment used in this simulator is shown in figure 3(b). The simulator displays a projection of the horizon, a star background, and the tethered Agena target model. In this simulation the Agena was not assumed to be a point mass as in the moving-base simulation. The rigid-body characteristics of the Agena as well as the Gemini were represented in detail in the equations of motion. First-order orbital effects were also included in the equations. The motion of the center of gravity of the tethered system was calculated in a local vertical axis system. Body axis control torques and forces were transformed to the local vertical axis system by the use of Euler parameters (ref. 2). Cable tension was calculated on the basis of the separation of the two vehicles in the local vertical system, and the angular momentum of each of the two vehicles was then determined. Body axis rates were then determined by using an inertia matrix.

The piloting task was basically the same in this fixed-base simulation as it was in the moving-base simulation with the addition of the effects of target motion and orbital effects. In addition to tests in which the system was spun up until 100 pounds (444.8 N) of tension in the cable was achieved, tests in which smaller system spin rates were established were also conducted. In these latter cases the pilot used only 2 to 5 seconds of lateral thrust. Cases which incorporated a 100-foot-long (30.48 m) cable with a 500-pound-per-foot (72.95 N/m) spring constant were also conducted. Since Agena motions were included in the fixed-base simulation, cases in which the Agena was initially oriented 90° to the cable were tested. Also, despinning of the system was tested.

RESULTS OF SIMULATIONS

Moving-Base Simulation

Figure 4 shows the results of a typical first attempt by an NASA test pilot using the Langley rendezvous docking simulator. All quantities are recorded as a function of time. For this first attempt, the pilot chose to use the second technique of extending the tether and yawing 26° before lateral thrusting. After the pilot applied his initial aft thrust, he started to yaw the vehicle around in an attempt to attain $\psi = 26^{\circ}$. At approximately 35 seconds after the initial aft thrust T_x, the vehicle reached the end of the cable as shown by the increase in the tension T record. The impact caused the vehicle to go forward and simultaneously swing the vehicle back to zero yaw. The pilot countered this motion by firing another aft impulse at 40 seconds while adding a yaw input. The vehicle reached approximately 30° in yaw, and the pilot held that angle as he applied lateral thrust until he hit the end of the cable at about 67 seconds. This impact swung the vehicle through zero yaw. The pilot tried to attain zero attitudes which maintain a steady tension. As can be seen from the tension record T in figure 4, the vehicle began to bounce in and out progressively harder and the pilot encountered more and more difficulty in controlling his attitude. This run had to be aborted when it appeared that the pilot could no longer control either the bounce of the cable or the attitudes. Several subsequent runs had to be made before the pilot could make a controlled smooth increase in tension and attain the desired spin-up rate. All pilots concluded that practice was required for this maneuver.

Figure 5 illustrates a typical run after practice by the test pilot in using the first procedure which takes advantage of the forward component of the lateral control thrusters. After the initial aft impulse T_x, the pilot waits until the cable is nearly taut before he applies a lateral thrust impulse to avoid an excessive impact as well as to start the spin-up of the system. In the run illustrated in figure 5, the first lateral impulse T_y occurred at approximately 28 seconds when there was about 6 feet (1.83 m) of slack remaining in the cable. He continued to apply small bursts of lateral thrust until he reached the end of the cable at about 35 seconds. At this point as his vehicle started toward the Agena, the pilot again applied an aft thrust to insure that he would not induce too much slack in the cable. This procedure again caused the two vehicles to separate, and during this time more lateral thrust was applied. The pilot quickly spun the system to what he felt was about 1 revolution per minute. From the tension record, it is noted that the vehicle was bouncing hard at the initial spin-up, but gradually by the application of aft thrust, the oscillations became smaller and smaller until at about 4 minutes the oscillations amounted to only about 10 pounds (44.48 N). In this maneuver, all the induced attitude motions ψ, θ, and ϕ are attributed to piloting techniques. Figure 5 indicates that the pilot could control the attitudes of the Gemini vehicle and damp the longitudinal oscillations. In addition to the fuel used to spin the system, the pilot used approximately 5 pounds (2.27 kg) of fore-and-aft fuel and 4 pounds (1.81 kg) of attitude fuel. This figure, however, does not show the pilot's best run and, with practice, this fuel expenditure was less.

Figure 6 indicates a sample run by the test pilot in which he used the second procedure successfully after practice. Again, the pilot starts yawing his vehicle to attain $\psi = 26^{\circ}$ soon after the initial aft impulse. At about 58 seconds he applies his first lateral impulse to start the spin-up of the system. As can be noted from the tension record T, he seemingly encounters more difficulty in initially spinning up the system while controlling the attitudes and the cable bounce. However, he finally damps out the system to a sufficient degree. These higher amplitude tension oscillations appear to be no real problem since the pilot still accomplished the desired task and used approximately the same amount of fuel. It is felt that since both procedures were successful, the selection between the two techniques would be a matter of pilot preference only.

Fixed-Base Simulation

Figure 7 shows a typical result from the fixed-base visual rendezvous simulator. The vehicles start with a 50-foot (15.24 m) separation between them and with the Gemini directly behind the Agena with all attitudes zero. The trace $s_{A,G}$ in figure 7 shows the distance of the Gemini from the Agena. This simulation was conducted for a 100-foot (30.48 m) cable and a 200 lb/ft (29.18 N/m) spring constant. The pilot initiates Gemini-Agena separation by making an aft thrust (F_X) 5 seconds after the problem was started. At approximately 20 seconds, with only about 10 feet (3.05 m) of slack remaining in the cable, the pilot starts the Gemini rotating by thrusting laterally (F_Y). After 37 seconds the Gemini hits the end of the cable for the first time. As the Gemini starts toward the Agena, the pilot thrusts aft again and continues his spin-up by thrusting laterally. The tension (T) record in figure 7 shows that the pilot spins the system up so that it has 100 pounds (444.8 N) of tension with about a 50-pound (22.24 N) oscillation. In comparison with the moving-base simulation, the amplitude of oscillation is considered to be high. However, the better control exhibited by the pilot in the moving-base simulator is attributed to the added input afforded the pilot by the motion. The oscillations experienced by the pilot were appreciable and provided a very good cue for thrust application. Roll, pitch, and yaw body rates of the Agena, p_A, q_A, and r_A, respectively, are also given in figure 7. One can observe that these rates are small and very easily controlled. The body rates of the Gemini, p_G, q_G, and r_G, which are given in figure 7, are also small and compare favorably with the results shown for the first procedure used in the moving-base simulator. The attitude thruster torques of the Gemini, M_ϕ, M_θ, and M_ψ, are given in figure 7.

To spin the system up to 100 pounds (444.8 N) of tension, approximately 15 pounds (6.8 kg) of fuel were used; this result is the same as that obtained in the moving-base simulator. One of the significant results from the Langley visual rendezvous simulator is that the motions of the Agena can be controlled by using only the attitude thrusters of the Gemini. Futhermore, even when the initial yaw angle of the Agena with respect to the Gemini was as great as 90°, it was no problem for the pilot to damp these large initial oscillations induced by the initial spin-up attempt. The pilot merely positioned his vehicle so that the Agena obtained a zero attitude when the cable was almost taut, he then thrusted aft and thus damped the high-attitude motions of the Agena. The problem was then reduced to the previous problem of spinning the system up when the Agena has small oscillations; the pilot had no problem doing this.

A simulation was conducted with a 100-foot (30.48 m) cable and a 500-lb/ft (72.95 N/m) spring constant. This configuration could be spun up and controlled; however, the fore-and-aft oscillation was exceedingly high. Part of this oscillation is attributed to a scaling and noise problem inherent in making the tension calculations in the analog computer. An exact determination of how well a pilot could damp this system could not be determined by using this simulation.

Figure 8 shows the results of a pilot using only 13 seconds of lateral thrust (F_Y) after he initiated the aft thrust (F_X) maneuver to start the separating of the vehicles. This simulation is for a 100-foot (30.48 m) cable and a 500-ft/lb (72.95 N/m) spring constant. Figure 8 shows a high-amplitude fore-and-aft oscillation. However, for a smaller spring constant (200 lb/ft (29.18 N/m) or less) and about 5 seconds of lateral thrust, this procedure becomes a desirable method of station keeping if the periodic fore-and-aft oscillation of the cable is not too disturbing and if a higher artificial gravity field is not desired. The most desirable feature of the short periods of lateral thrusting time (approximately 5 seconds) is that the fuel expenditure is only about 2 or 3 pounds (0.91 or 1.36 kg).

The most significant part of the maneuver shown in figure 8 begins to occur at about 250 seconds. This point is the one at which the pilot begins the despin portion of the maneuver. In the simulation shown in figure 8, the pilot used 9 pounds (4.08 kg) of total fuel to spin the system to induce about 80 pounds (377.8 N) of tension. In order to despin the system to the point at which the pilot can maintain a slack cable, the pilot used an additional 6 pounds (2.72 kg) of fuel. For the higher spin rates, 10 seconds or greater thrust time, it was difficult for the pilot to determine his spin plane. Therefore, the pilot wasted fuel by applying lateral thrust when the Gemini thrust vector was not alined with the spin plane. For the case in which the pilot used 5 seconds or less of lateral thrust initially, the fuel expenditure was about 3 pounds (1.36 kg) to spin-up and 1 to 2 additional pounds (0.45 to 0.91 kg) to despin.

The case of the application of only 2 seconds of lateral thrust would be sufficient if the pilot initiated the separation of the vehicles slowly enough. However, the pilots who flew the simulator usually hit the end of the cable too hard to use only 2 seconds of lateral thrust. This condition too is dependent upon the magnitude of the spring constant. The smaller the spring constant, the smaller the lateral thrust required.

Figure 9 shows theoretical and actual fuel consumption for a pilot maintaining arbitrary levels of tension up to 100 pounds (444.8 N). As can be seen from the figure, the pilot can perform the task by using only 2 or 3 pounds (0.91 or 1.36 kg) more of translation fuel than the optimum (shown as a solid line). In addition, his attitude fuel ranges from 0.5 pound (0.23 kg) for low tensions up to 4 pounds (1.81 kg) for 100 pounds (444.8 N) of tension.

CONCLUDING REMARKS

As long as the rotation of two tethered bodies is such that the maximum moment of inertia of each of the connected bodies is alined with the spin vector, the system is neutrally stable.

This study has shown that a pilot can, with practice, spin the system up to any desired tension. This result was observed with both the moving-base simulator and the fixed-base simulator; however, in the moving-base simulator, the pilot could damp the fore-and-aft oscillation to an imperceptible level.

The translational fuel required in both simulators was only slightly greater than that theoretically required for spin-up, and only a small amount of additional attitude fuel was needed.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 17, 1967,
125-19-01-06-23.

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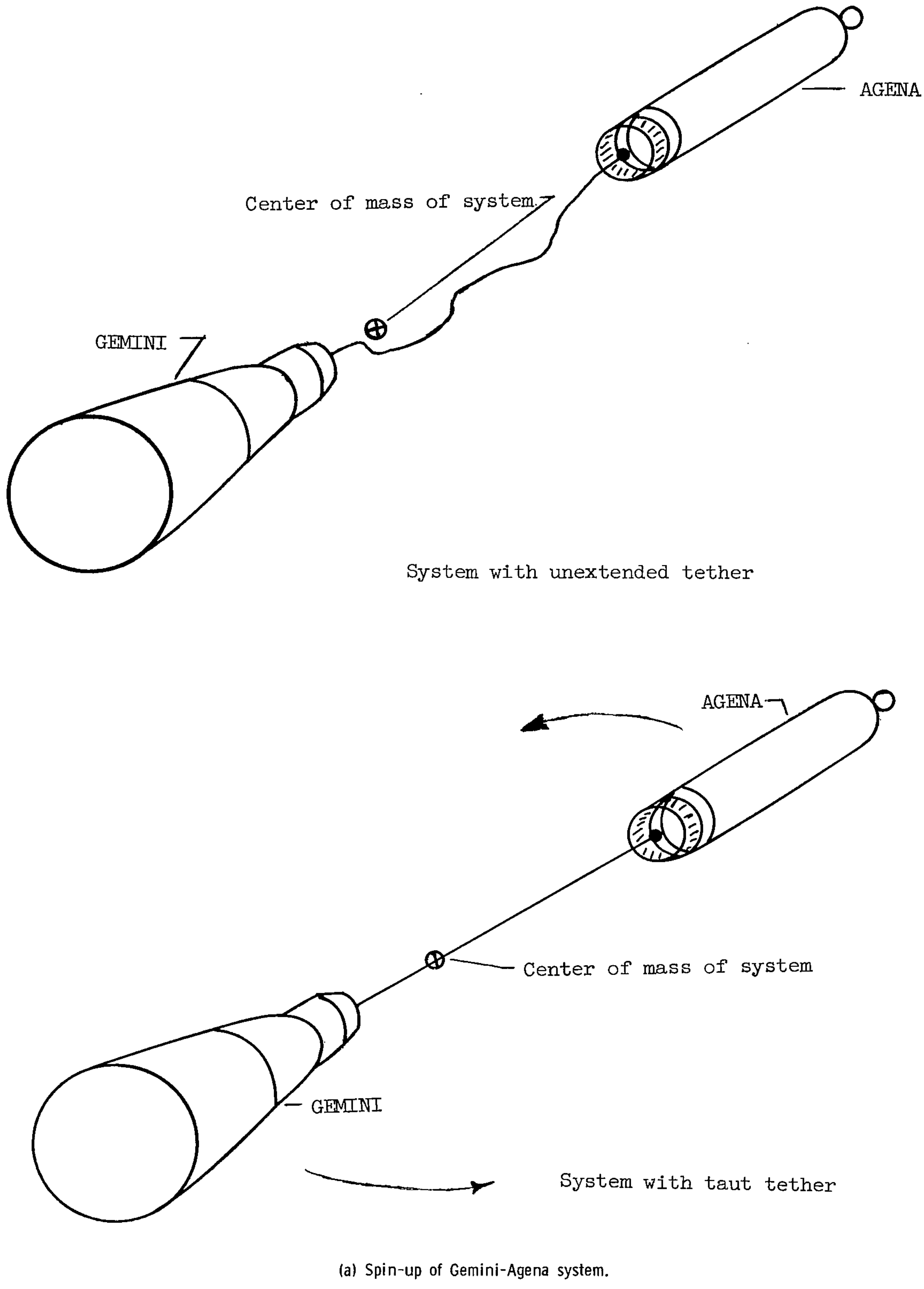
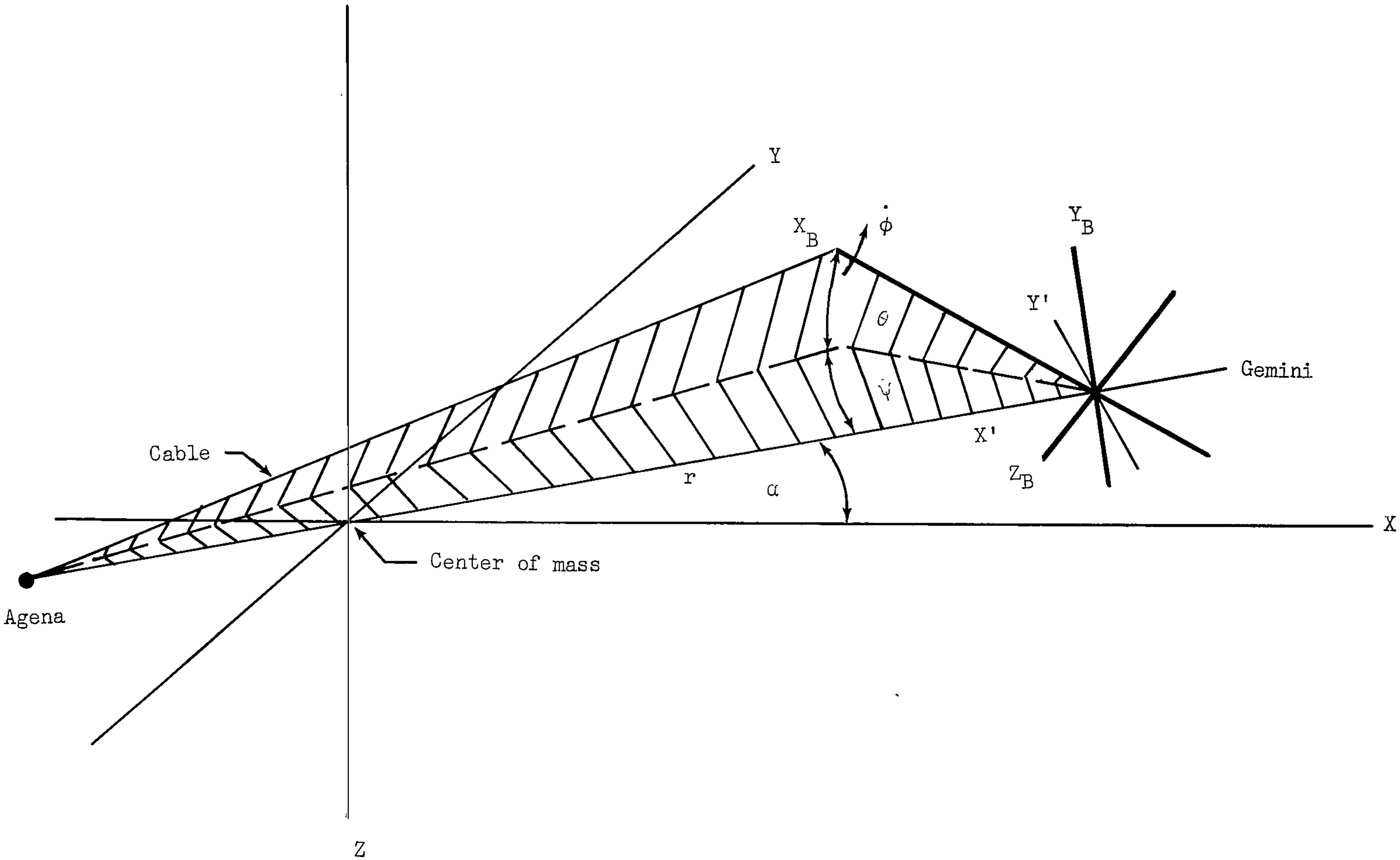
2. Goldstein, Herbert: Classical Mechanics. Addison-Wesley Pub. Co., Inc. (Reading, Mass.), c.1959.



(a) Spin-up of Gemini-Agena system.

Figure 1.- System configuration.



(b) Assumed coordinate system.

Figure 1.- Concluded.

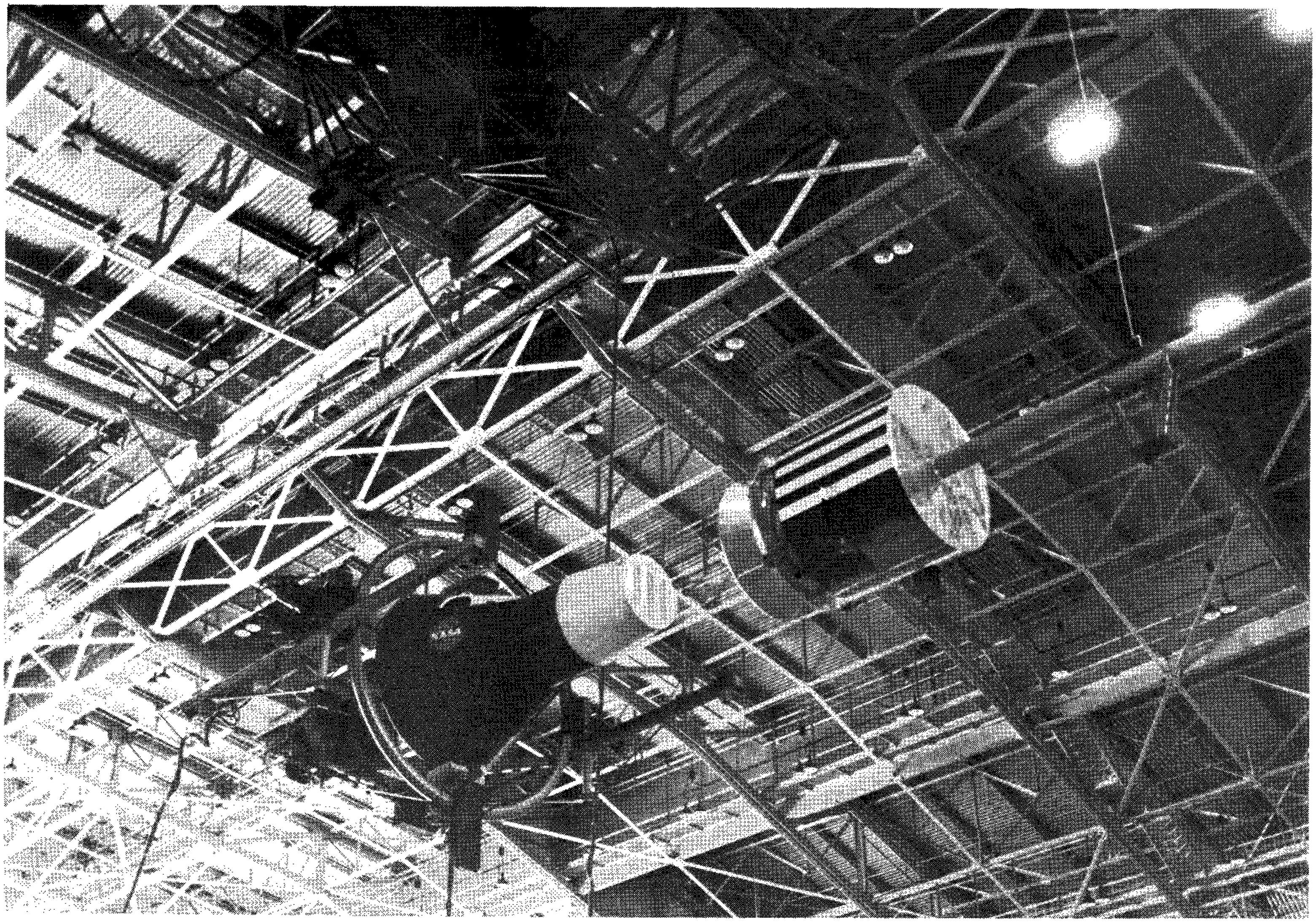


Figure 2.- Langley rendezvous docking simulator.

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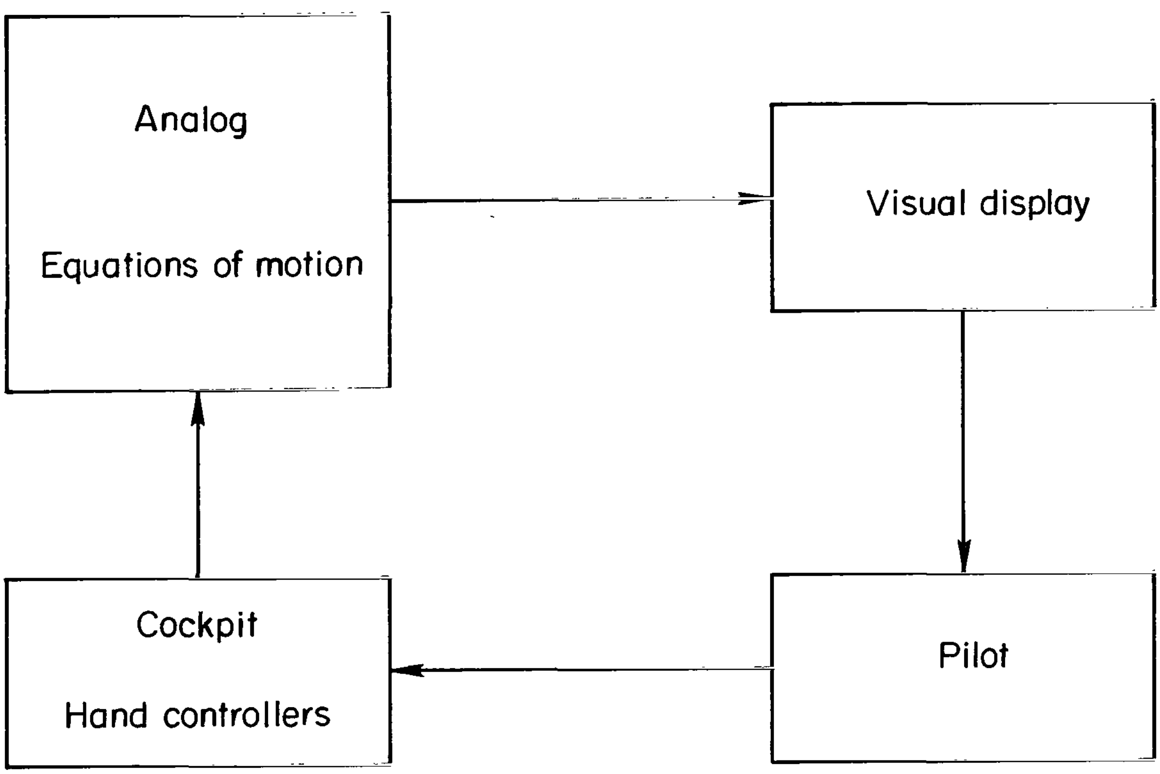
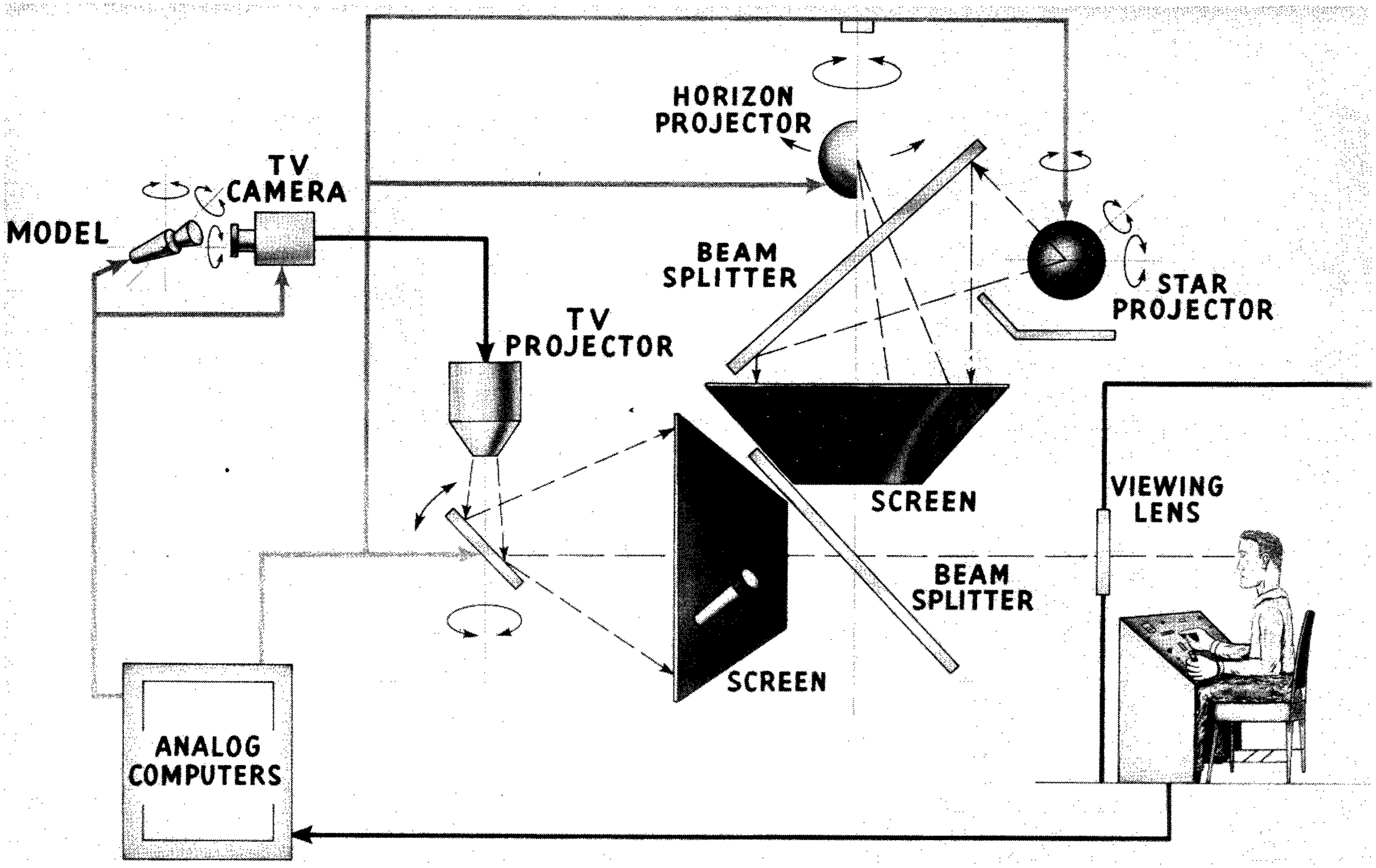


(a) Complete simulation approach.

Figure 3.- Simulator construction.



(b) Langley visual rendezvous simulator.

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Figure 3.- Concluded.

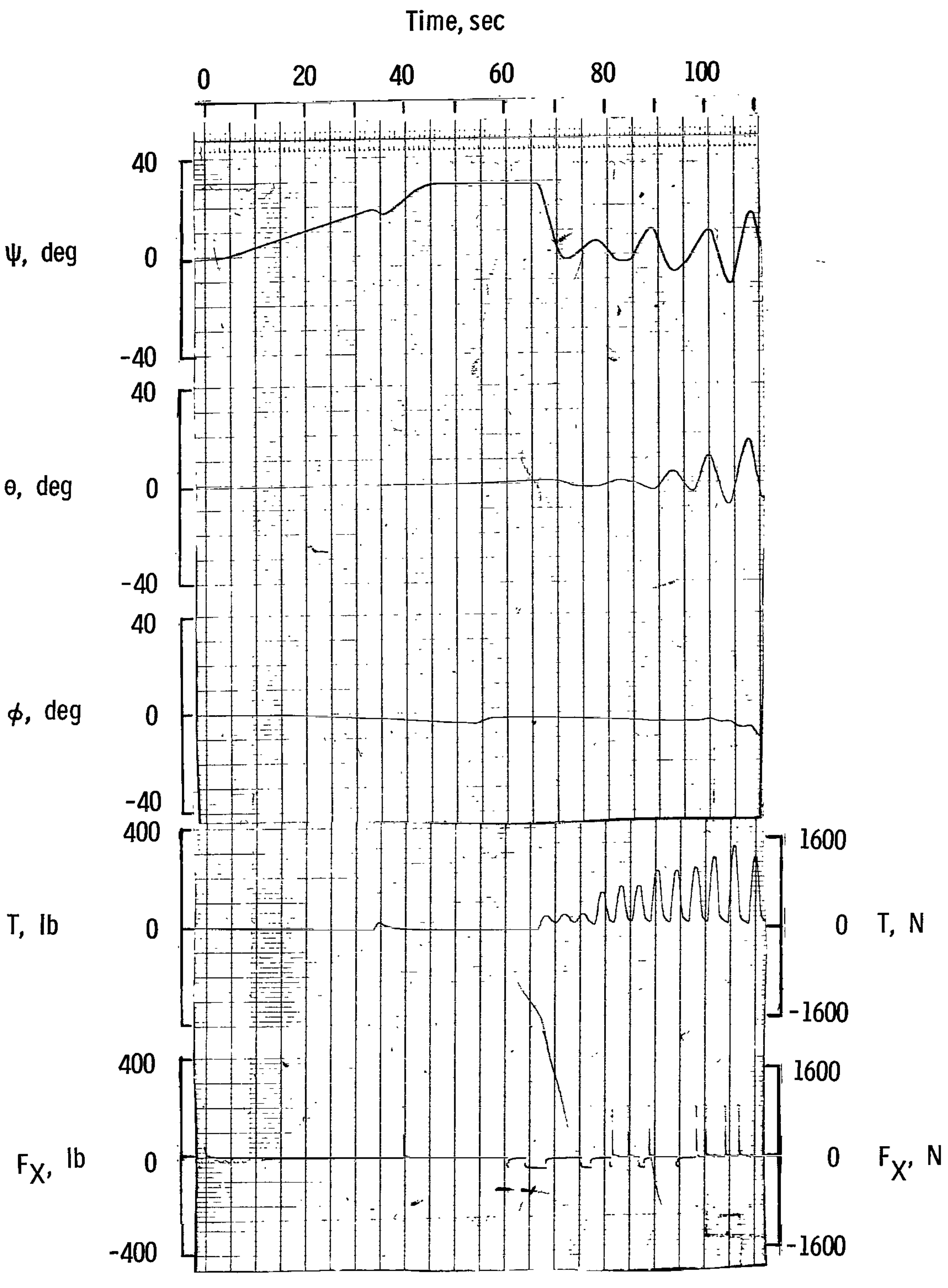

Figure 4.- Sample run of test pilot.

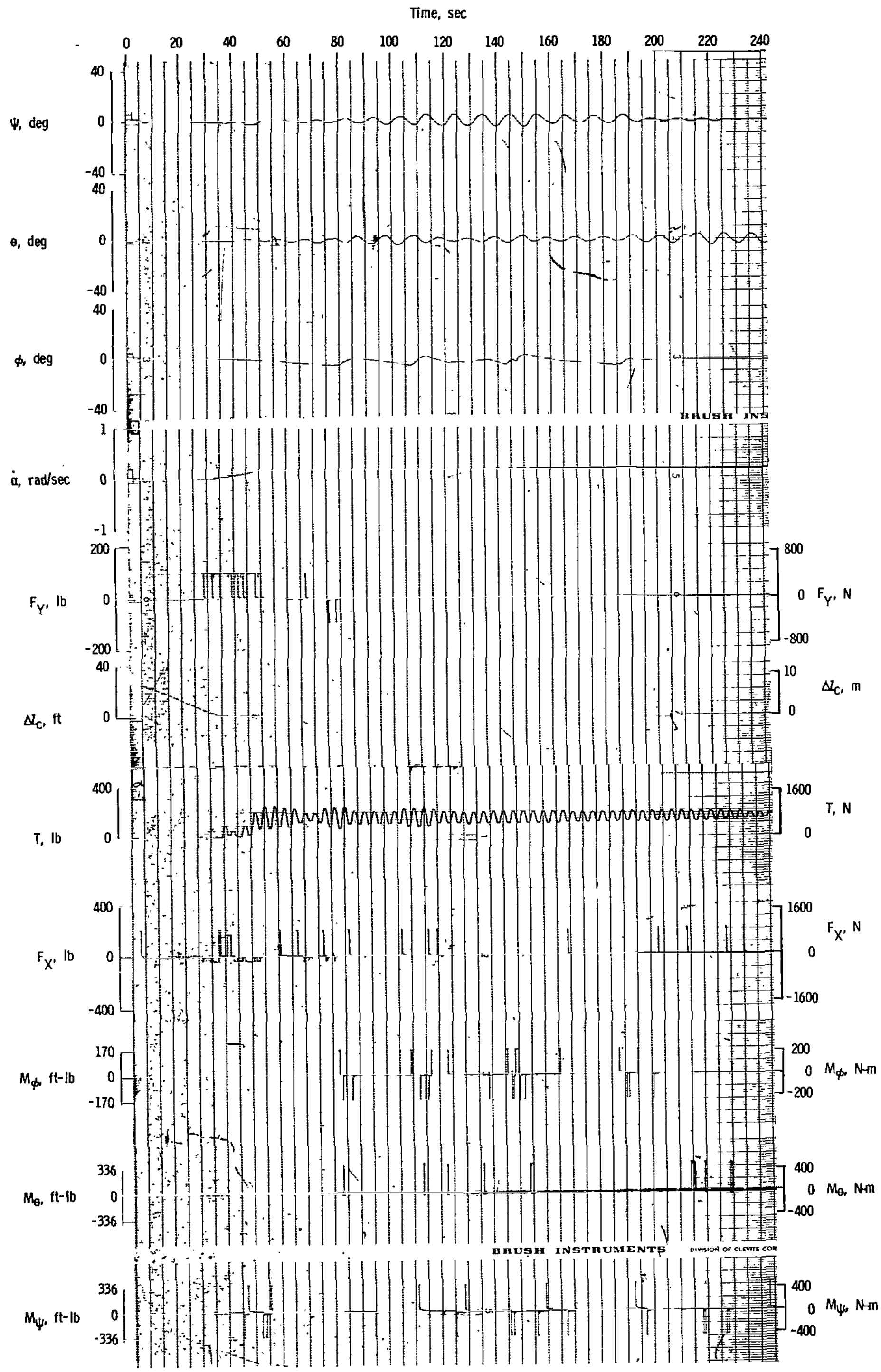

Figure 5.- Sample run of test pilot.

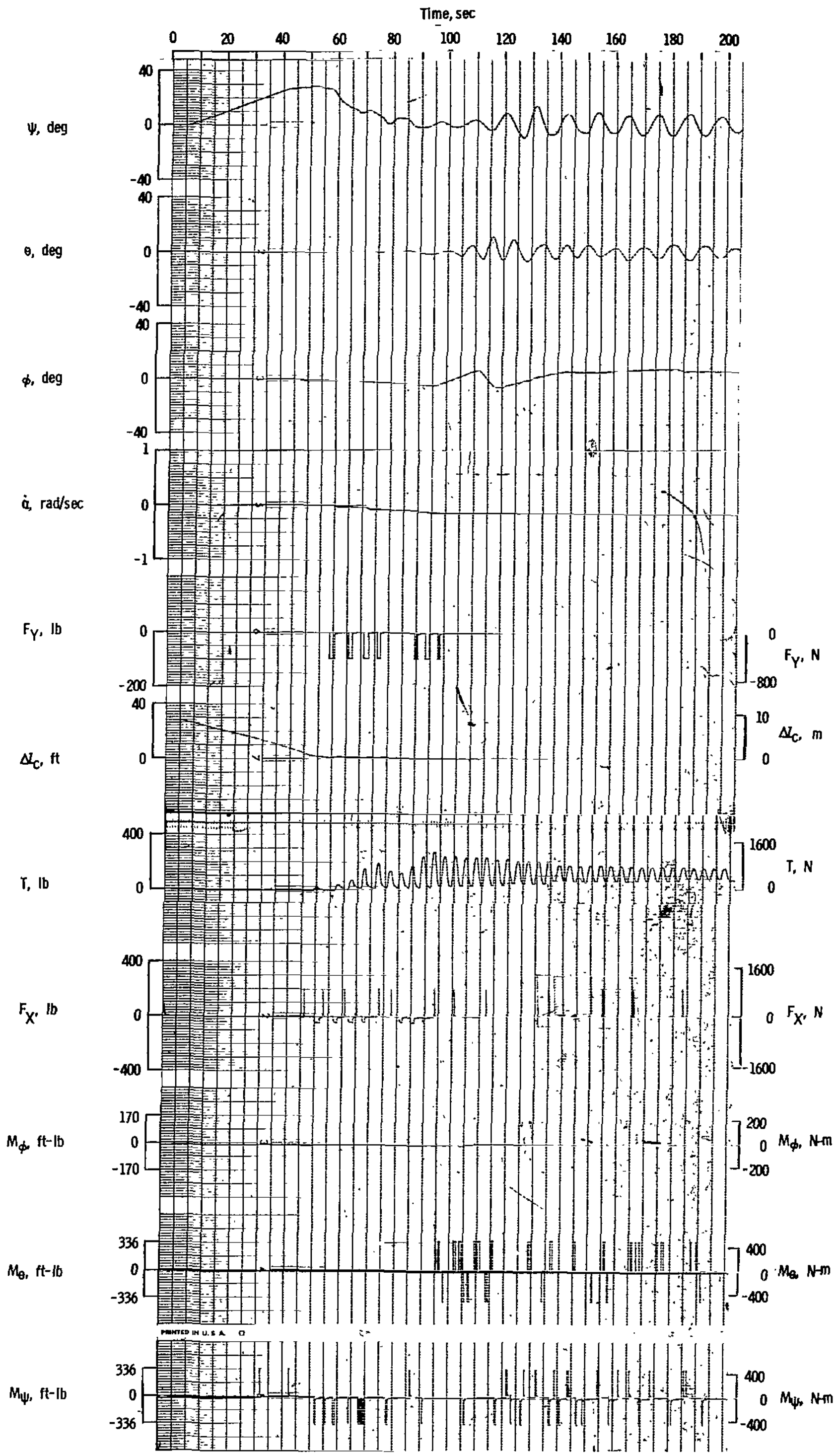

Figure 6.- Sample run of test pilot.

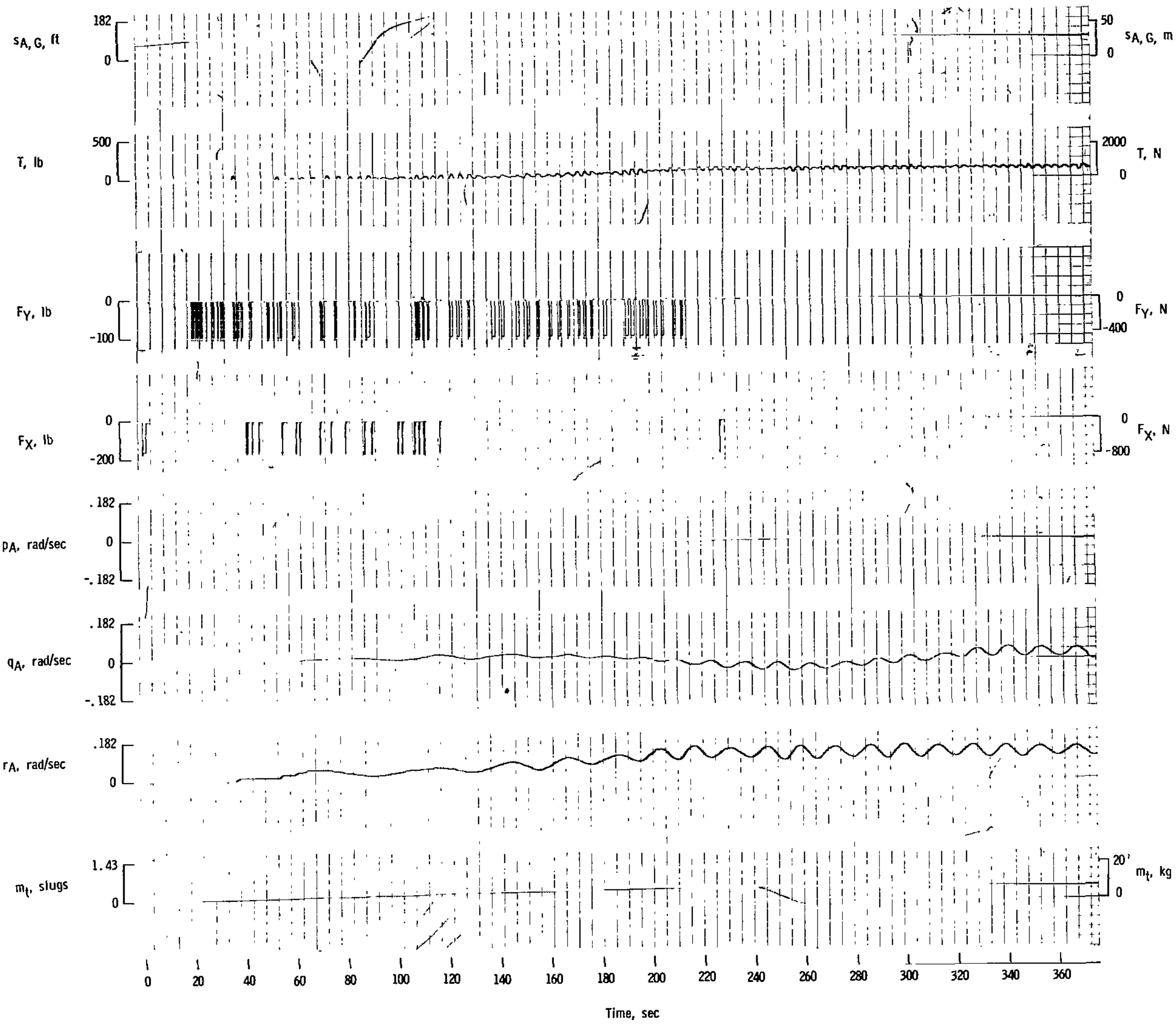

Figure 7.- Sample pilot run from Langley visual docking simulator.

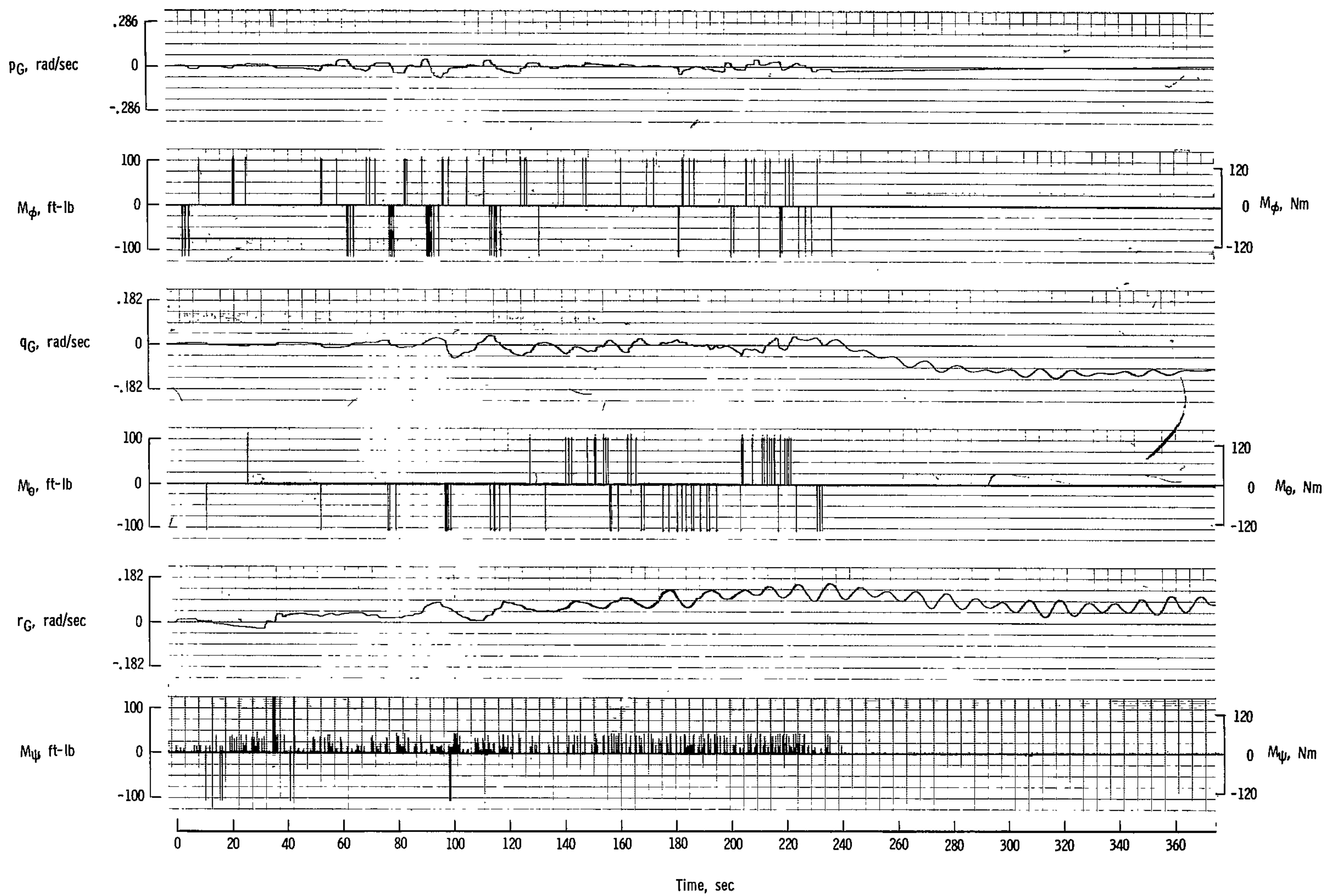

Figure 7.- Concluded.

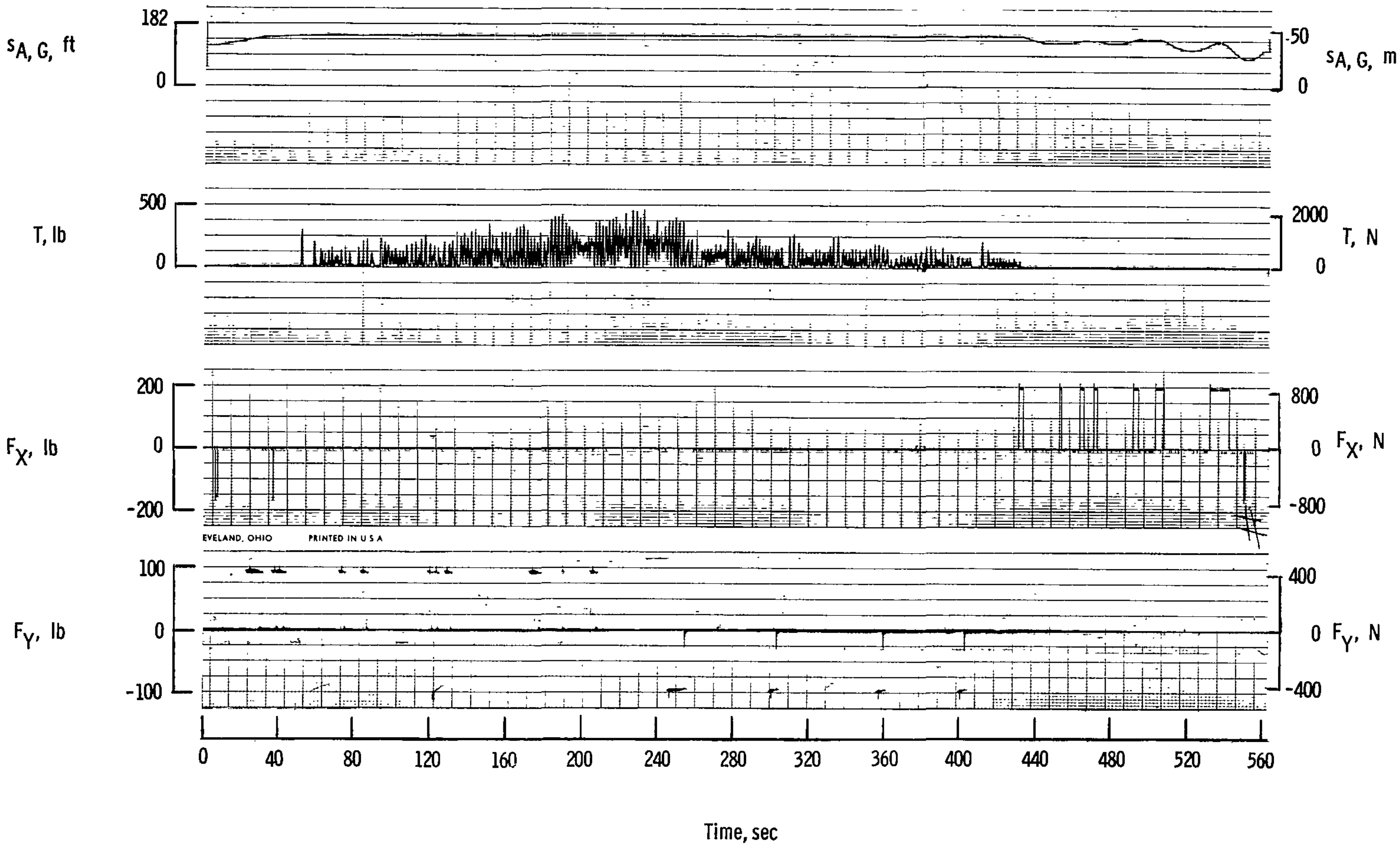

Figure 8.- Despin maneuver on Langley visual docking simulator.

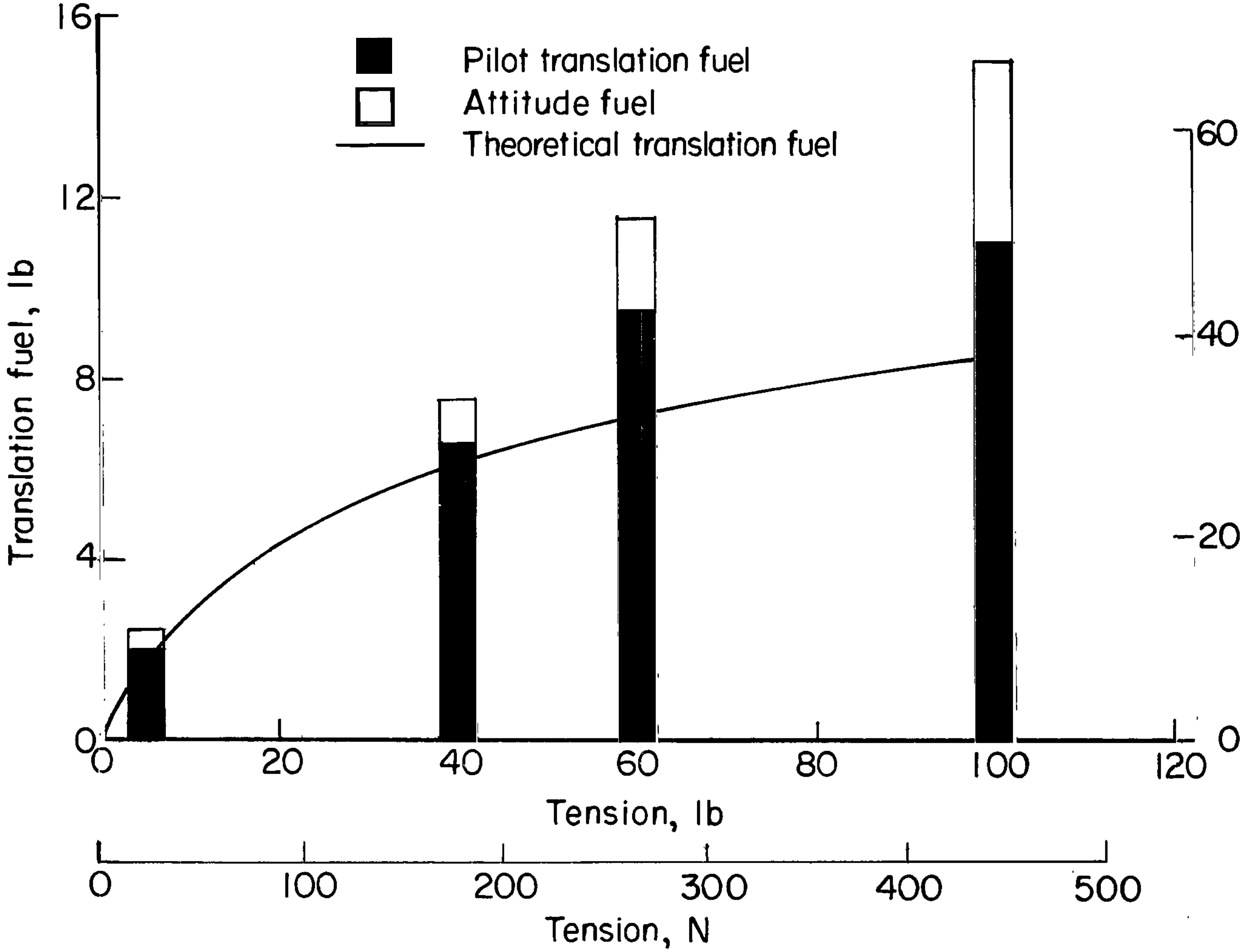

Figure 9.- Comparison of pilot fuel use with theoretical fuel use.

NASA-Langley, 1967 — 31 L-5365

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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